UCRL-91791
PREPRINT

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P. Clapis
R. Roser
K. J. Reed
Q. C. Kessel

This paper was prepared for submittal to
Nuclear Instruments and Methods.

November 14, 1984

Lawrence Livermore National Laboratory

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P. Clapis and R. Roser,

Department of Physics, The University of Connecticut, Storrs, CT 06268

K. J. Reed,

Lawrence Livermore National Laboratory, Livermore, CA 94550

and Q.C. Kessel

Department of Physics and The Institute of Materials Science, The University of Connecticut, Storrs, CT 06268.

ABSTRACT

Investigations of the energies of electrons emitted as a result of collisions between very heavy ions and atoms show that a significant number of the electrons have a continuous spectrum of energies that is difficult to associate with separated atom levels. This has caused speculation as to the origin of some of these electrons: These include the possibility of autoionization occurring during the collision while the molecular potentials are changing, autoionization involving more than two electrons and autoionization from a multiplicity of poorly defined states interacting at a specific distance of closest approach. The present measurements detect the continuum electrons in coincidence with ions scattered to a specific angle, thereby determining the impact parameter dependence of the underlying excitation mechanism.

1. Introduction

The electron emission spectra from heavy ion-atom collisions often consist of a continuous part upon which the characteristic Auger peaks may be observed. For collision systems such as Kr - Kr, Kr - Xe and Xe - Xe, the continuous portion of the spectrum is dominant for collision energies ranging from 100 keV to several MeV. For the Kr - Kr and Kr - Xe systems this continuum has been investigated (1-7) for electron energies from 100 to 1000 eV, an energy range which does not include the normal Auger lines. For the Xe - Xe combination, M-shell vacancy production would give rise to Auger peaks between 300 and 600 eV and these together with satellite lines from highly ionized states may account for most of the emitted electrons. The non-characteristic nature of the Kr - Kr electron emission spectra has been the source of speculation. Gordeev and others (1,3,5) suggest that a molecular orbital (MO) level demoted during the collision might be filled from other, promoted orbitals while the nuclei are still in close proximity. The electrons emitted from such an MO process could have energies in the observed range. Another suggestion, by Woerlee and co-workers, is that the higher-energy continuum electrons might be the result of direct coupling with the continuum (2). The present paper suggests that the continuum may be the result of interactions among a multiplicity of MO levels interacting at a well-defined distance of closest approach.

Dynamic coupling and uncertainity broadening of the outer-lying states makes it impossible to attribute a well-defined energy to an electron in one of these levels during the collision. Therefore any filling of inner vacancies during the collision will result in autoionized electrons having a continuous range of energies.

2. Coincidence Measurements

Figure 1 shows the cross section for non-coincident electron emission versus electron energy for Kr^+ - Kr collisions. The continuous portion between 100 and 1000 eV is under consideration here; however, the insert with a linear ordinate is shown to better display the L Auger portion of the spectrum. The apparent rise between 900 and 1200 eV in the Gordeev data was attributed to L electrons, but it is more likely due to poor suppression of background electrons. Coincidence measurements for 50 keV collisions (5) together with the present 200 keV data are shown in fig. 2. These data are obtained by simultaneous detection of the ejected electrons with ions scattered to a fixed angle. This establishes the impact parameter dependence of the excitation. From measured values of the incident ion energy and the scattering angle, a distance of closest approach, R_o, may be calculated (8). For example, the 5^o data in Fig. 2a correspond to an R_o value of about 0.71 a.u. and for larger values of R_o, no continuum electrons are observed. The 7^o data correspond to R_o = 0.65 a.u. and thus the threshold for the excitation may be taken to be about 0.6 – 0.7 a.u. The spectra are most pronounced in the 50 keV, 15^{o} – 18^{o} data and the 200 keV, 3^{o} data corresponding to R_o values in the range of 0.5 – 0.6 a.u. The adiabatic, one-electron molecular potential curves calculated for the Kr – Kr system by Eichler and co-workers (9) are shown in fig. 3. The boxes in the range of internuclear separation of 0.5 – 0.7 a.u. show couplings by means of which various n = 3 electrons might be promoted to higher levels. More details of this promotion are shown in the curves of fig. 4 which were calculated by the same method (10). The independent particle model is most applicable to inner-shell electrons, where the effect of the strong nuclear charge dominates other interactions, and is generally less applicable to outer shell electrons where electron-electron interactions are more important. Nevertheless, we note that the series of avoided crossings experienced by the adiabatic sigma gerade curves for distances between 0.5 and 0.7 a.u. suggest a pathway for the dynamic promotion of electrons from a large number of different orbitals during the collision. As these distances correspond well with the R_o values for the production of the continuum electrons, their origin is probably associated with this promotion. Several other factors may contribute to the nature of the electon continuum. Within the MO model, a vacancy filled during the collision can result in a variable energy for the ejected electron because of variations in the MO energies as R changes during the collision (1). Furthermore, the energies of the outer-lying orbitals from which the inner-shell vacancies may be filled are poorly defined. Uncertainty broadening and dynamic coupling during the collisions make it impossible to assign an exact energy to an outer-shell electron during the collision. Multielectron effects can also produce ejected electrons with non-characteristic energies, even within the independent-electron framework. (For example, two electrons may be promoted simultaneously by a sigma orbital. Energetically an autoionization may occur as soon as the sum of their energies is sufficient for a single ionization.) Autoionization has also been observed wherein two electrons share the customary single-electron Auger energy (11,12). An improved calculation including multiconfiguration interaction and relativistic effects (13) may be necessary in order to better explain the phenomenon.

In summary, the threshold behavior for the continuum electron production indicates that a specific promotion is responsible for the production of the M-shell vacancies, while the nature of the continuum itself may be due to multiple causes. This conclusion is in contrast to that of earlier investigators who concluded that the electrons were due to the filling of vacancies demoted by a single, well defined MO (the diabatic $4p\pi$ MO formed during the collision by dynamic coupling of the 4π and 3π ungrade orbitals) (1,2,5).

The Xe – Xe system appears to be one for which a more conventional explanation is possible; fig. 5 shows three spectra. The upper one is a non-coincidence spectrum from 0.5 MeV collisions showing three poorly resolved peaks. Below it is a coincidence spectrum showing those electrons from collisions for which the incident ion was scattered through 10^{o} (14). For this value of the impact parameter the coincidence data show the same general features as the non-coincidence data. At the bottom are shown the more conventional Auger peaks excited by protons (15). Identification of these proton excited M Auger lines has been made (15) and it appears that the 340 and 440 eV Xe excited peaks may be attributed to the decay of satellite states.

This research has been supported by National Science Foundation grant PHY-8406117. We are grateful, as well, for the use of computation facilities at Lawrence Livermore National Laboratory; work performed, in part, under the auspices of th U. S. Department of Energy by the LLNL under contract number W-7405-ENG-48. The authors also wish to acknowledge helpful discussions with Professors J. D. Garcia. and A. Russek. John Gianopoulos helped in taking the data.

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FIGURE CAPTIONS

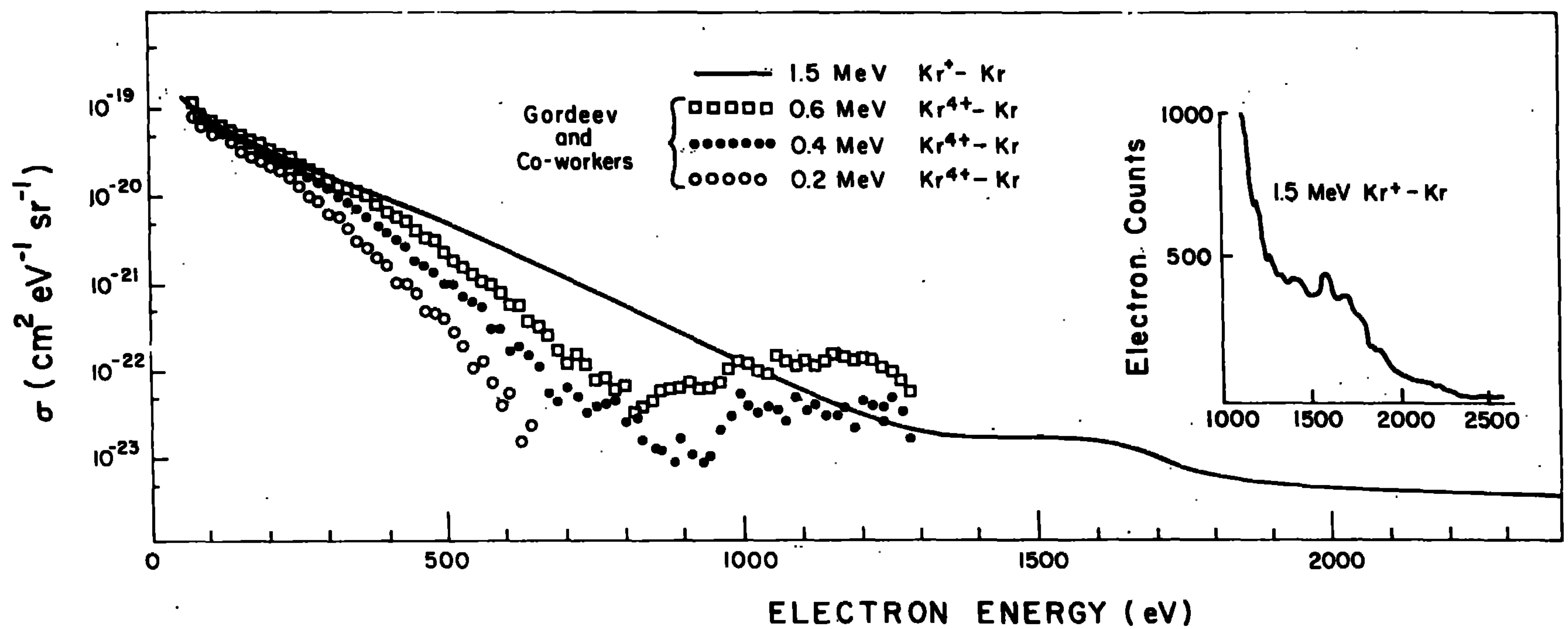
FIGURE 1. Doubly differential cross sections for production of electrons in Kr – Kr collisions. The 0.2, 0.4 and 0.6 MeV data are from reference 1 for which the electron emission angle was 123°. The present 1.5 MeV data have been normalized to ref. 1 at 100 eV and the emission angle for these data was 90°.

FIGURE 2. The electron coincidence counts are plotted versus electron energy: a) reference 5; b) present work.

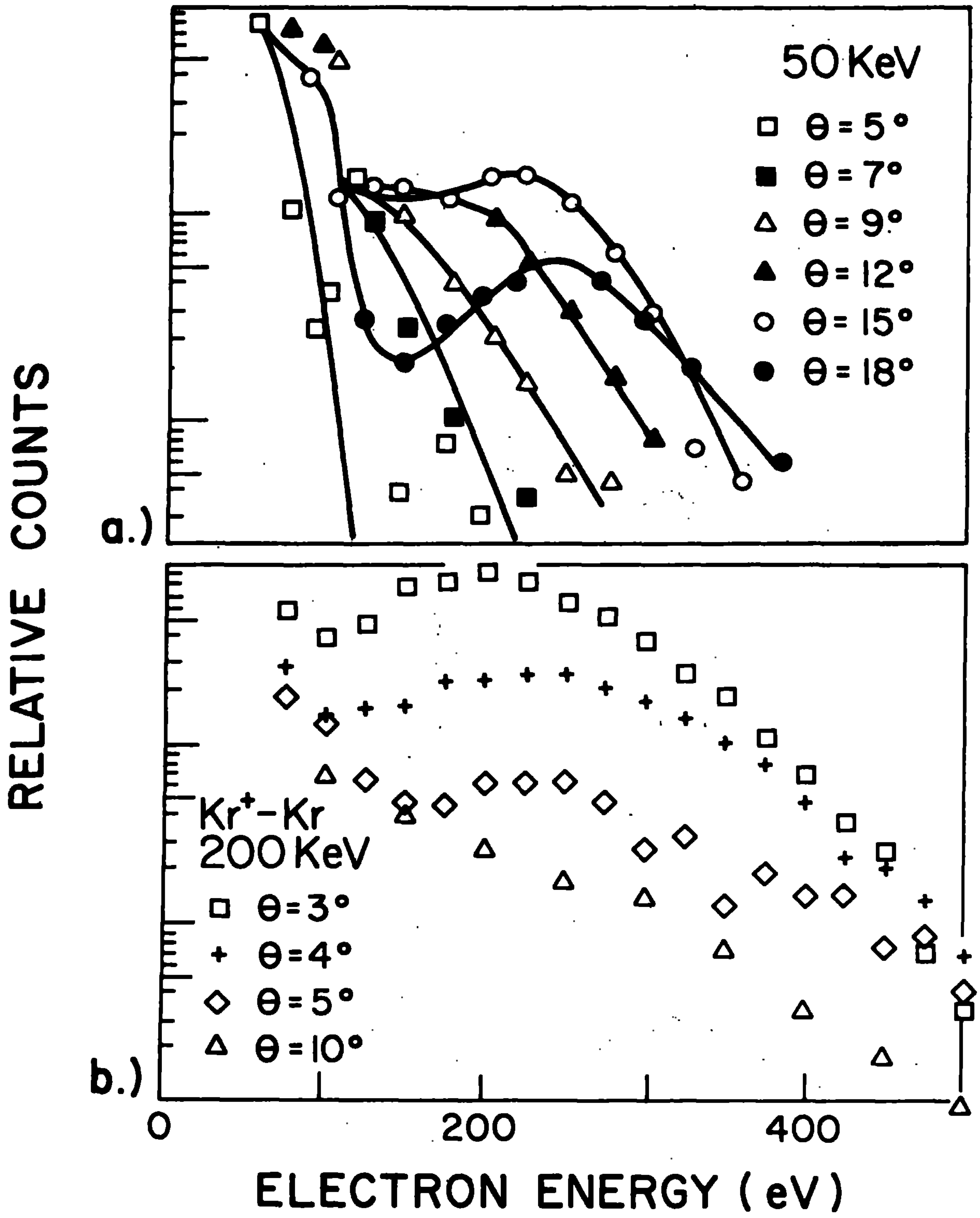
FIGURE 3. Correlation diagram for the Kr – Kr system. Gerade and ungerade potentials are shown as solid and dashed lines, respectively (from reference 9).

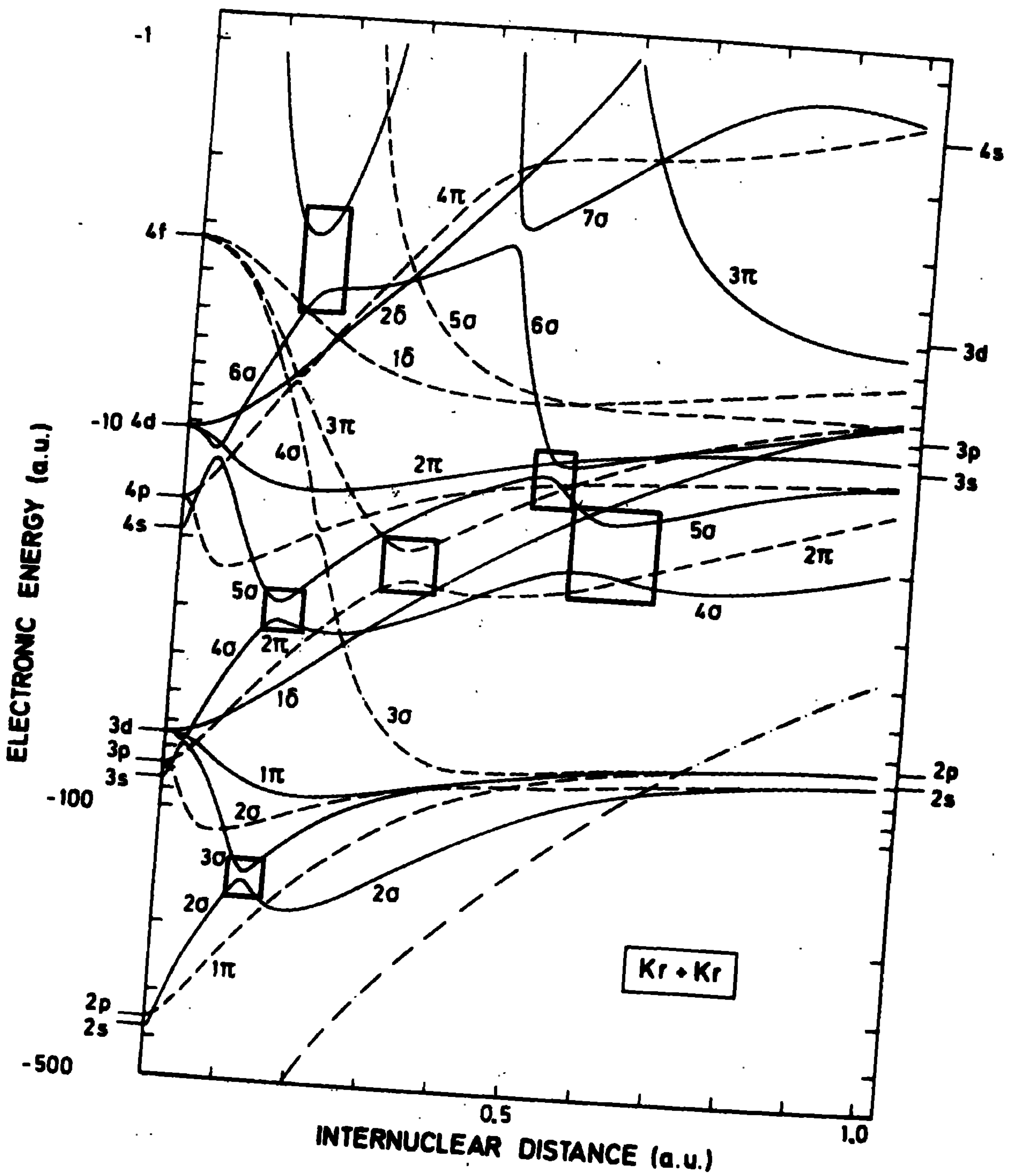
FIGURE 4. An extension of the calculations in figure 3.

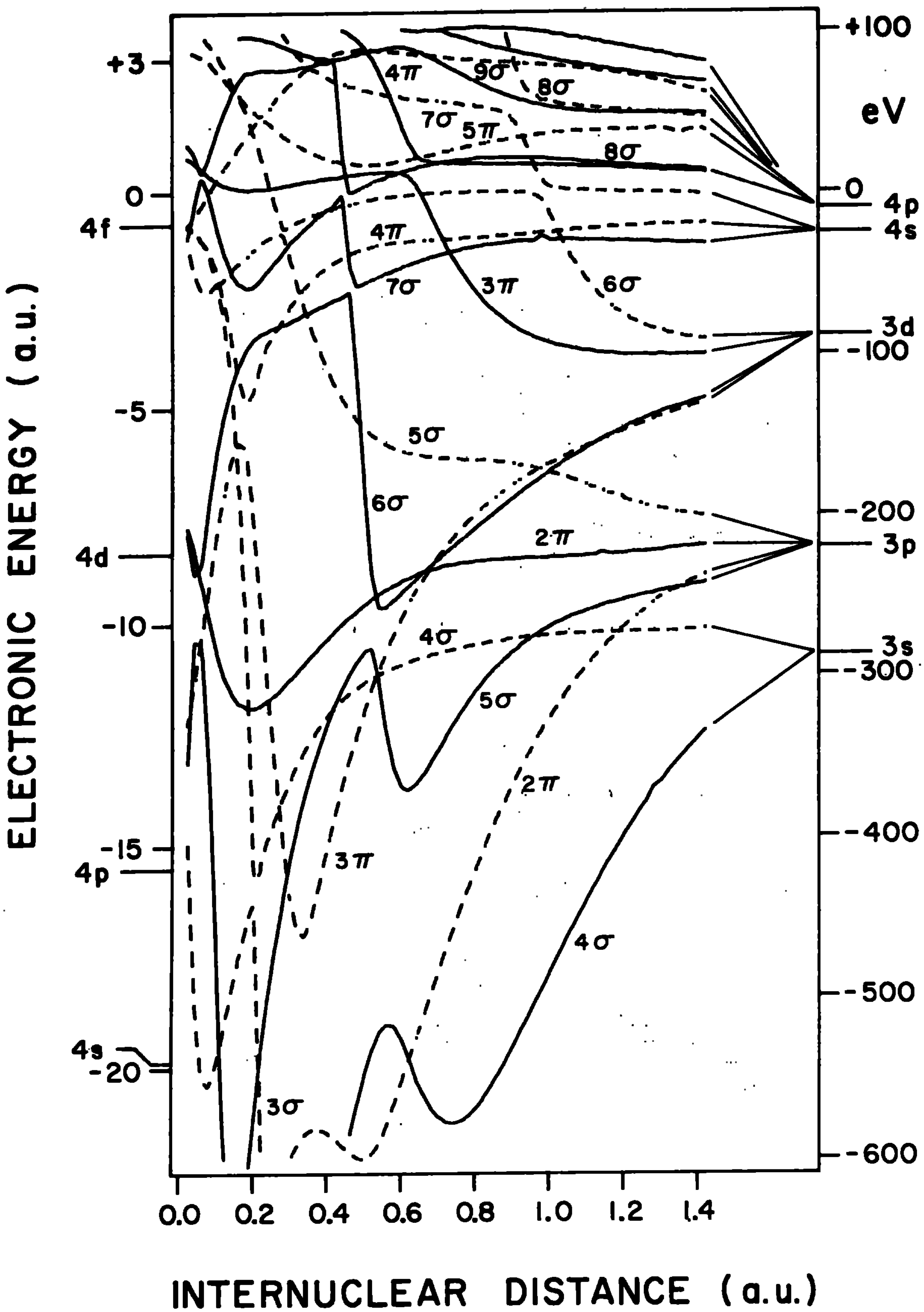
FIGURE 5. Electron counts versus electron energy for Xe^+ – Xe collisions (present work) and H^+ – Xe collisions (reference 15).

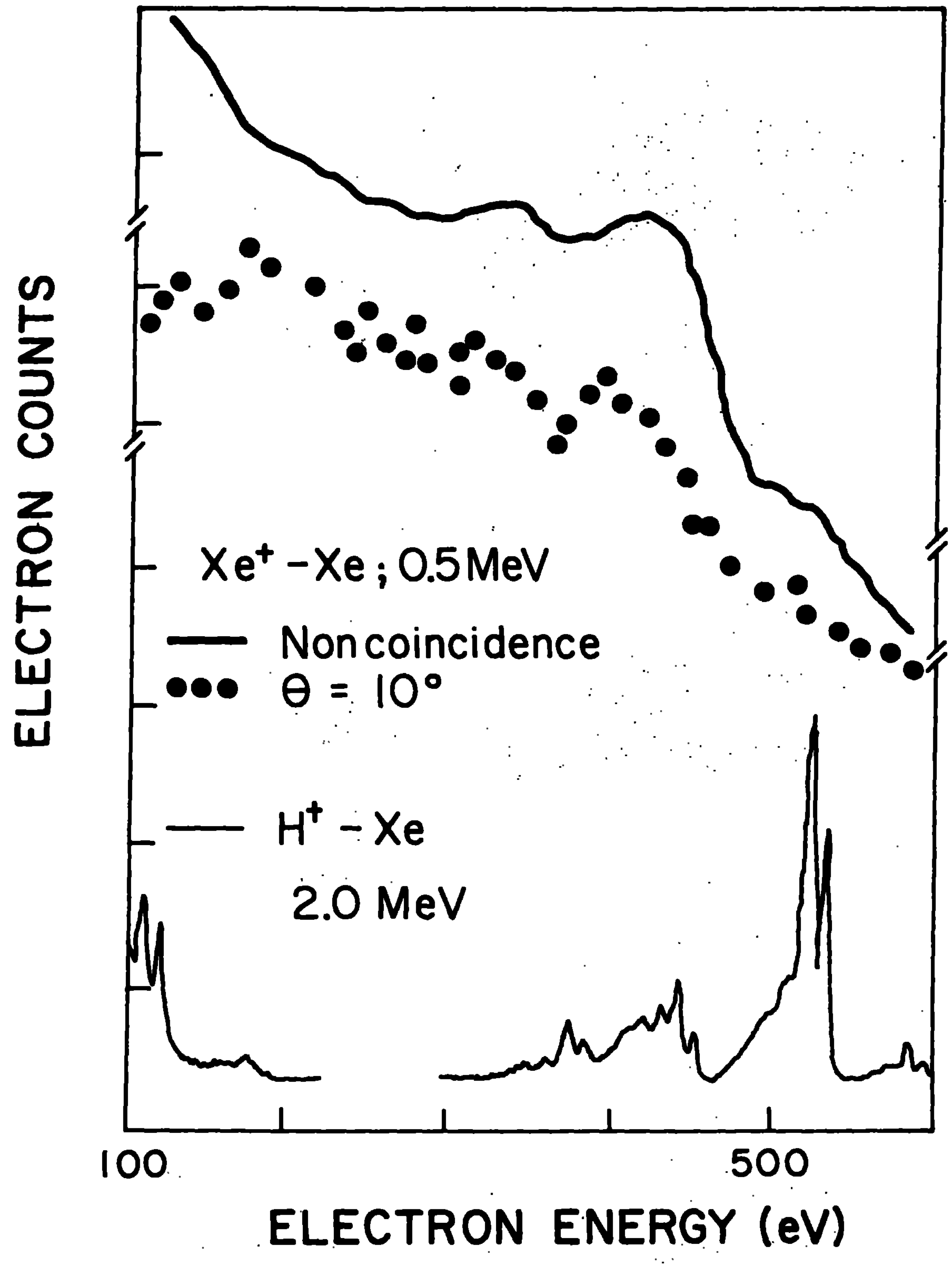


1.5 MeV Kr+ - Kr
Gordeev and Co-workers
0.6 MeV Kr4+ - Kr
0.4 MeV Kr4+ - Kr
0.2 MeV Kr4+ - Kr
σ (cm2 eV-1 sr-1)
10-19
10-20
10-21
10-22
10-23
0
500
1000
1500
2000
ELECTRON ENERGY (eV)
Electron Counts
1000
500
1000
1500
2000
2500
1.5 MeV Kr+ - Kr


50 KeV
θ = 5°
θ = 7°
θ = 9°
θ = 12°
θ = 15°
θ = 18°
a.)
Kr⁺-Kr
200 KeV
θ=3°
θ=4°
θ=5°
θ=10°
b.)
RELATIVE COUNTS
0
200
400
ELECTRON ENERGY (eV)


Kr + Kr
ELECTRONIC ENERGY (a.u.)
INTERNUCLEAR DISTANCE (a.u.)
-1
-10
-100
-500
0.5
1.0
4f
4d
4p
4s
3d
3p
3s
2p
2s
6σ
4σ
5σ
2π
1δ
3π
2δ
5σ
6σ
7σ
4π
3σ
1π
2σ
3σ
2σ
1π


ELECTRONIC ENERGY (a.u.)
INTERNUCLEAR DISTANCE (a.u.)
eV
+3
0
-5
-10
-15
-20
4f
4d
4p
4s
+100
0
-100
-200
-300
-400
-500
-600
4p
4s
3d
3p
3s
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
4π
9σ
8σ
7σ
5π
8σ
4π
7σ
3π
6σ
5σ
6σ
2π
4σ
5σ
2π
3π
4σ
3σ


ELECTRON COUNTS
Xe+ - Xe ; 0.5 MeV
Noncoincidence
θ = 10°
H+ - Xe
2.0 MeV
100
500
ELECTRON ENERGY (eV)